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CHARACTERIZATION OF NON-LTE GOLD PLASMAS IN CONTROLLED CONDITIONS WITH FINITE T_r

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Understanding the charge state distribution of gold plasmas, especially in conditions far from local thermodynamic equilibrium ("non-LTE conditions"), is among the issues in ICF hohlraum physics research. Detailed models of these plasmas have historically disagreed by several charge states under a given set of conditions; simplified models in radiation-hydrodynamics codes disagree more. This impacts the accurate prediction of radiation coupling within the hohlraum. Nova laser data for uniform gold plasmas¹ at $T_e=2.2$ and $T_r<0.05$ keV and additional data from plasmas inside hohlraums² have not resolved all of the issues. Here we report experiments using the Omega laser to obtain data over a wider parameter space. Gold samples embedded in Be disks expand under direct laser heating to $n_e\sim 10^{21}\text{cm}^{-3}$ with T_e from 1 to 3 keV. Some of the disks are placed within hohlraums, providing a finite radiation temperature $T_r\sim 150$ eV. Densities are measured by imaging of plasma expansion; temperatures by Thomson scattering and K-shell spectroscopy of co-mixed KCl tracers. Emission spectroscopy of Au 5-3 emission from 2.9-4.2 keV provides charge state distribution information. We summarize results to date and remaining issues.

I. INTRODUCTION

Accurate prediction of target behavior in indirect-drive inertial confinement fusion requires a detailed understanding of the driver coupling to the hohlraum and the subsequent coupling of the hohlraum radiation to the capsule. Both processes are mediated by the low-density, non-LTE blowoff plasma which expands from the walls and eventually fills the hohlraum.³ The electron density, X-ray emission and power absorption in this plasma depend in turn upon the plasma's ionization balance and charge state distribution. For laser-driven hohlraums there is particular interest in the physics below the critical density $n_e < n_c \sim 10^{22}\text{cm}^{-3}$.

Most hohlraums use high-Z wall materials to provide adequate albedo and energy confinement, but accurate modeling of high-Z non-LTE plasmas is challenging both in terms of physics and in terms of computational requirements, particularly when the non-LTE model must be included in a much larger radiation-hydrodynamics

simulation. Comparisons of state-of-the-art non-LTE codes have greatly illuminated this topic in recent years.

A comparison of 9 different model predictions⁴ of the mean ionization $\langle Z \rangle$ versus temperature $0.8 < T_e < 2.8$ keV for gold plasmas at $n_e = 10^{20}\text{cm}^{-3}$ found a total spread among the models of 14-19 charge states out of a mean $\langle Z \rangle$ ranging from ~ 40 to ~ 55 . Some simulations will have gold ions in wrong shells, with correspondingly large errors in the predicted X-ray absorption, emission, and transport. The more reliable codes clustered together better, with a spread of only 5-10 charge states, but the reality is that most rad-hydro codes do not have the luxury of using those state-of-the-art calculations.

Benchmarking experiments carried out at the Nova laser have improved the situation somewhat. A study of laser-heated, Be-tamped Au foils at $n_e = 6 \times 10^{20}\text{cm}^{-3} \pm 20\%$ and $T_e = 2.2\text{ keV} \pm 10\%$ analyzed the $n=5$ to $n=3$ transitions between 3.3 and 3.5 keV, from which $\langle Z \rangle = 49.3 \pm 0.5$ was inferred.^{1,5} These data were taken without a hohlraum ($T_r < 0.05$ keV). Other experiments have

characterized the hohlraum blowoff directly, providing information on the ionization balance with finite T_r but with density and temperature gradients present.² An additional set of experiments studied the ionization balance of Au at $n_e \approx 10^{12} \text{ cm}^{-3}$ in coronal equilibrium.⁶

A second set of code comparisons was recently completed, and there is now better convergence of the models near the 2.2 keV data point.⁷ However, the coronal data are not in good agreement with the models, and at higher densities the temperature dependence and effects of radiation temperature still need to be assessed.

Here we present initial results from a new set of experiments using the Omega laser over a broader electron temperature range (1-3 keV), and at radiation temperatures of $T_r < 0.05 \text{ keV}$ and $T_r \approx 150 \text{ eV}$. The basic method used on Nova¹ has been replicated, with the addition of a hohlraum surrounding the Be disk which provides the radiation flux for the $T_r \approx 150 \text{ eV}$ case.

II. EXPERIMENTAL CONFIGURATION

The targets for these experiments consisted of Be disks approximately 11 μm thick and 300-400 μm in diameter, containing a thin, 200 μm diameter embedded layer of either Au or co-mixed Au:KCl. As shown schematically in Figure 1, approximately half of the targets were placed inside tungsten-coated hohlraums 1.2 mm in diameter, 1.6 mm in length, with fully open laser entrance holes. With these short-length hohlraums, the geometry at Omega allows up to 6 beams to hit each side of the disk directly, while up to 30 beams heat the hohlraum walls.

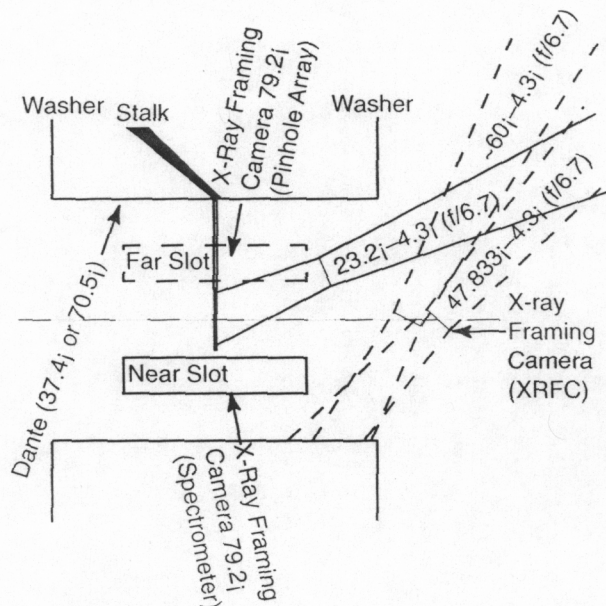


Figure 1: Experimental configuration, including target, beam and diagnostic geometry.

The laser pulse timing is shown in Figure 2. All beams used 2ns square pulses. One or two beams on each side run early to preheat the disk, burn through the Be and expand the Au. One, two or four beams on each side then heat the disk to the desired electron temperature, and the hohlraum (if present) is heated concurrently. Finally, a probe beam at either 2ω or 4ω runs from +1.5 ns.

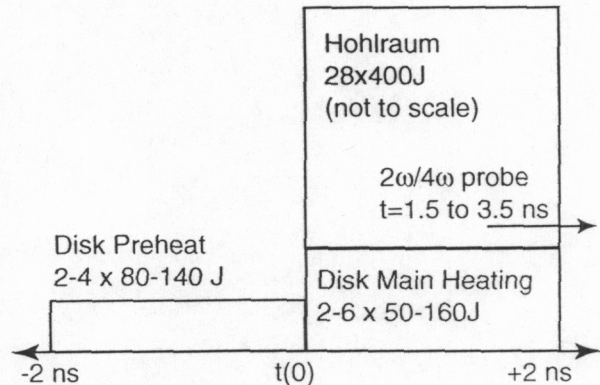


Figure 2: Laser pulse timing diagram.

Figure 1 also shows the lines of sight of the principal diagnostics. Gated pinhole cameras with axial and quasi-perpendicular (79.2°) views provide images of the Au disk and information on the disk's expansion (density) and uniformity. An absolutely-calibrated filtered X-ray diode array (Dante)⁸ measures the hohlraum X-ray flux over ~ 10 spectral bands, providing a measurement of the radiation temperature T_r . Another framing camera at 79.2° uses a convex cylindrically-bent imaging RAP crystal spectrometer (TSPEC)⁹ to measure the Au:KCl emission from the sample through 2 slots in the side of the hohlraum. The slots prevent the TSPEC from seeing the hohlraum wall behind the sample. TSPEC's spatial resolution separates the sample emission from the hohlraum emission. Scattered light from the $2\omega/4\omega$ probe beam travels to an optical/UV spectrometer, which records the Thomson scattering spectrum as a measurement of the electron temperature, T_e , using the same methods as in the Nova experiments^{1,2}.

Figure 3 shows the experiment in action. The disk has not expanded measurably in the radial direction.

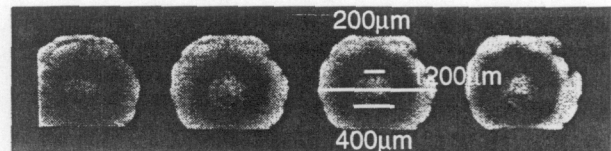


Figure 3: Face-on X-ray framing camera pinhole images of disk within hohlraum at $t \sim 0.3 \text{ ns}$. Bars show the diameter of the hohlraum (1200 μm), disk (400 μm) and buried Au layer (200 μm), respectively. Each image is gated for $\sim 100 \text{ ps}$; time between images is $\sim 80 \text{ ps}$.

III. PLASMA CONDITIONS

Following the Nova experiments, it is expected that the sample expansion reaches conditions of interest by $t = 0.7$ ns.¹ Because there was no measurable radial expansion of the sample, the sample density was determined from the axial expansion relative to the initial areal density. The spatially-resolved X-ray lines from the sample span 400 μm . After accounting for the TSPEC slit width (80 μm at magnification 2 = 120 μm point-spread) and the 10.8° viewing angle relative to the 200 μm samples (40 μm parallax), the axial expansion is estimated as 240 μm . The Au layer had an initial density of 160 $\mu\text{g}/\text{cm}^2$, so the Au density in the expanded sample is $2.1 \times 10^{19} \text{ cm}^{-3}$, and the electron density (assuming a $\langle Z \rangle$ of 45) is $9.4 \times 10^{20} \text{ cm}^{-3}$. Some samples included 96 $\mu\text{g}/\text{cm}^2$ of KCl in addition to the Au, contributing an additional $3.3 \times 10^{20} \text{ electrons}/\text{cm}^3$ (at $\langle Z \rangle = 17$). Thus the total electron density is $1.3 \times 10^{21} \text{ cm}^{-3}$ for the Au:KCl co-mixed samples. We estimate a 20% shot-to-shot variation in n_e and a 30% single-shot uncertainty. A more detailed analysis is in progress. These densities are 1.5 to 2.0 times higher than the Nova data, but since the ionization balance in this regime is not strongly dependent on density, the data should be comparable. In particular, these experiments also meet the ionization-equilibrium conditions of the Nova experiments.¹

The 2ω and 4ω Thomson Scattering systems, commissioned at Omega in 2002 and 2003, respectively, provided data on the electron temperature for the plain-disk targets. (Two initial attempts to record Thomson Scattering spectra from samples within hohlraums were unsuccessful.) The Thomson Scattering beam was operated from 1.5 to 3.5 ns, after the density and spectroscopic data were acquired. For intensities near the published Nova data, the Omega Thomson Te data agree to within the 10-20% uncertainties on the measurements. Omega data obtained at lower intensities is roughly consistent with a $T_e \sim I^{2/3}$ scaling expected theoretically.¹⁰ In particular, based on a fit to the available (preliminary) Omega data, we infer $T_e = 1.0$ keV for $I = 1.7 \times 10^{14} \text{ W}/\text{cm}^2$, at the lower end of our data range. Future analysis of the KCl lines in the emission spectra for the Au:KCl co-mix samples should provide an independent check on Te.

For targets with hohlraums, the radiation temperature was measured by the Dante absolutely-calibrated filtered X-ray diode array to be 175 eV $\pm 5\%$ during the time of interest. Because these hohlraums have both wide-open laser entrance holes and multiple diagnostic slots, the hohlraum wall only covers 61% of the solid angle seen by the sample. Therefore the X-ray flux incident on the sample is reduced by 39% from what would be seen if the sky were 175 eV in all directions. The effective radiation

temperature is therefore roughly 155 eV. The M-band channel on the Dante (filtered for X-rays $> \sim 2$ keV) contributes up to 18% of the total flux during the time range of interest.

IV. GOLD EMISSION SPECTRA

The TSPEC snout mounted on a standard Omega X-ray framing camera produces 4 gated spectra per shot. The individual frames are staggered in time. The framing camera was timed to the laser pulse to within 200 ps by observing the turn-on of the hohlraums and by observing flash X-ray emission from thin KCl coatings on the outer surface of some Be disks. For the spectral range of interest the transit time of the gate pulse was 150 ps, and the pulse width was ~ 100 ps. The spectral resolving power $E/\Delta E$ is at least 100 in the range 2.9 to 3.5 keV and at least 80 out to 4.4 keV.

More than 30 spectra of acceptable quality have been obtained, from more than 15 shots, with timings between $t = 0.5$ ns (when the sample density has reached conditions of interest) and $t = 1.5$ ns (when the Thomson Scattering probe beam begins to perturb the plasma). The data for disk-only targets span the laser intensity range from 1.7 to $8.4 \times 10^{14} \text{ W}/\text{cm}^2$, with T_e ranging from 1.0 to 2.8 keV. The comparable ranges for disk-in-hohlraum targets The laser intensity range are $I = 1.7$ to $6.6 \times 10^{14} \text{ W}/\text{cm}^2$ and T_e from 1.0 to 2.3 keV (not including the effects of the hohlraum radiation field).

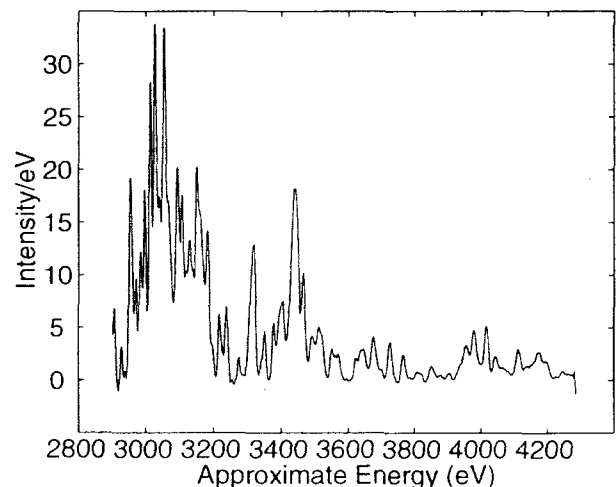


Figure 4. Non-LTE emission of Au heated at $1.7 \times 10^{14} \text{ W}/\text{cm}^2$ ($T_e \approx 1.0$ keV).

Because of the large number of spectra and the wide range of plasma conditions, the data reduction and the detailed analysis are not yet complete. Figure 4 provides a preliminary example of the spectral data from an Au-only plain disk at $I = 1.7 \times 10^{14}$ ($T_e \approx 1.0$ keV). Relative calibration of this spectrum is in progress. The TMAX

3200 film response (wedge curve) has been incorporated, as has the relative spectral width of the pixels in the scanned film; however, other energy-dependent corrections have not been applied yet. As a result, detailed line-ratio and charge-balance analyses are not yet meaningful. Meanwhile, the wavelength scale for the spectra are being determined using an instrument geometry / raytracing code calibrated by H-like and He-like KCl spectral lines from targets containing KCl. The wavelengths for Au-only samples (as in Figure 4) are believed to be accurate to about 30 eV, and line identification is underway.

V. DISCUSSION

Despite the preliminary status of the data analysis, significant information is already being extracted. The spectra vary considerably with temperature, providing evidence for the anticipated shifts in ionization balance as either T_e or T_r is varied. Consider the published Nova data,¹ where there is strong emission in the range 3.3 to 3.5 keV and $\langle Z \rangle$ was determined to be about 49 (Zn-like) at $T_e = 2.2$ keV. In contrast, Figure 4 shows that at $T_e \approx 1.0$ keV the emission is primarily from the 3.0 to 3.2 keV range. These lower-energy X-rays are presently believed to be 5-3 transitions in lower ionization stages of Au, suggesting that $\langle Z \rangle$ is significantly less than that found at $T_e = 2.2$ keV. However, the 5-3 transition radiation has not disappeared entirely, so there must remain significant populations with, at minimum, $Z > 42$. It is anticipated that further analysis of the plain-disk spectra will yield a fairly precise $\langle Z \rangle$ for $T_e \approx 1.0, 1.5, 2.0$ and 2.8 keV at $T_r \approx 0$. Analysis of the hohlraum data referenced to the disk data at identical laser intensity will yield a second data set identifying the effects on $\langle Z \rangle$ of the additional hohlraum $T_r \approx 150$ eV over a comparable range of T_e .

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